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Introducing the best model for estimation the monthly mean daily global solar radiation on a horizontal surface (Case study: Algeria)

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ABSTRACT

In this study, 11 empirical models are developed correlating the monthly mean daily global solar radiation on a horizontal surface with monthly mean sunshine records and air temperature data for six Algerian cities (Algiers, Oran, Batna, Ghardaia, Bechar, and Tamanrasset). In order to indicate their performance, seven statistical parameters were introduced; coefficient of determination (R^2), mean percent error (MPE), mean absolute percent error (MAPE), mean bias error (MBE), mean absolute bias error (MABE), and root mean square error (RMSE).

The results obtained in this study confirm the previous studies, which have indicated that the sunshine based models are generally more accurate than air temperature based models. According to the results, the best performances are obtained by the cubic and the quadratic regression models for the six Algerian stations. Moreover, these two regression models can be used for the proposed generalized models for predicting the monthly mean global solar radiation in other Algerian locations in the absence of the measured solar radiation data.

Contents

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1. Introduction

Solar energy is considered to be a safe, effective and economic energy resource, having the potential to be one of the major energy sources in the near future [1]. The amount of solar energy (or solar radiation) available on the earth's surface depends on astronomical, physical, meteorological and geographical parameters such as extraterrestrial radiation, atmospheric transmittance, latitude, inverse relative distance between the Earth and the Sun, sunset hour angle, the actual duration of sunshine, relative humidity, ambient temperature and cloudiness at relevant locations [2,3].

For the design and selection of solar energy conversion systems, the knowledge of accurate global solar radiation data is extremely important for the optimal design and prediction of the solar system performance [3]. The best solar radiation data on the place of interest would be that measured at this specific site continuously and accurately over the long term. Unfortunately, for many developing countries like Algeria, solar radiation measurements are not easily available due to financial or technical limitations. Therefore, it is so important to elaborate solar radiation data based on high performance models.

In order to meet the needs of these studies, several approaches have been developed for estimating the surface solar radiation, such as remote sensing retrievals [4,5], single-layer and multi-layer radiative transfer models [6–9] and a number of empirical models based on surface meteorological data. The empirical models are the most popular, because of its low computational cost and accessible inputs [10].

Several empirical formulas have been developed to calculate the global solar radiation based on three main parameters; sunshine hours [11,12], temperature-based models [13,14], and cloud-based models [15,16]. The highest precision is expected when using sunshine hours as the predictor [17–19]. Air temperature based models are also widely used, since air temperature data are readily available [20].

Based on sunshine and air temperature records, there are numerous studies have been published about estimation of monthly mean global solar radiation for different regions of the world in the literature.

The first correlation for estimating monthly mean daily global solar radiation on horizontal surface was carried out by Angstrom [11], this regression equation-related monthly average daily radiation to clear day radiation in a given location and average fraction of possible sunshine hours. To solve the difficulty in obtaining the clear day solar radiation data, Prescott [12] suggested using the extraterrestrial radiation to replace it, and the modification in this way resulted in the formation of the Ångstrome–Prescott, which has been the most convenient and widely used correlation for estimation of solar radiation based on sunshine duration. After that, many empirical models have been derived from this model to estimate monthly mean daily radiation from commonly observed meteorological.

Bakirci [21] reviewed several empirical correlations which relate global solar radiation to other climatic parameters such as sunshine hours, maximum temperature and relative humidity, and found that sunshine duration is the most commonly used parameter for estimating global solar radiation. While Khatib et al. [22] gave an overview of the solar energy modeling techniques, and classified it to linear, nonlinear and artificial intelligence models. They presented the sunshine ratio, ambient temperature and relative humidity as the most correlated coefficients for modeling solar energy. Furthermore, Besharat et al. [23] collected and reviewed empirical models available in the literature for estimating global solar radiation in order to classify them into four categories, i.e., sunshine-based, cloud-based, temperature-based, and other meteorological parameter-based models. Moreover, they evaluated their accuracy and applicability on the basis of seven statistical error indicators by comparing it with the measured data of Yazd city (Iran).

Despite the amount of these works done, no much empirical correlation has been found for Algerian locations in the literature. Chegaar and Chibani [24] applied two models for estimating monthly mean daily global radiation on a horizontal surface to four Algerian locations. While Salmi et al. [25] developed three sunshine based models to estimate the monthly mean global solar radiation on horizontal surface for four different Algerian locations. Koussa et al. [26] carried out a statistical comparison of 10 existing models for estimating monthly mean daily global and diffuse solar radiation in three main Algerian sites (Bouzareah, Ghardaia, and Adrar). For most locations in Algeria with unavailable data of global solar radiation, general models for predicting the global solar radiation are needed.

The main objectives of this study are: (i) establishing 11 empirical models with new coefficients of correlation (6 based on sunshine records and 5 based on air temperature data) for 6 Algerian locations. (ii) By using six statistical indicators, the new models were evaluated in order to introduce the best model for each station, (iii) and to develop generalized models for estimating the global solar radiation data in other Algerian locations in the absence of the measured data.

2. Data and methodology

2.1. Data

2.1.1. Study area

Algeria situated in the center of North Africa along the Mediterranean coastline, between latitudes 19° and 38° North and longitudes 8° West and 12° East, has an area of 2,381,741 km^2. This geographic location of Algeria signifies that it is in a position to play an important strategic role in the implementation of solar energy technology in the north of Africa [27].

Fortunately, Algeria has an enormous potential of solar energy. As shown in Table 1, the potential of daily solar energy is important; it varies from a low average of 4.66 kWh/m^2 in the north to a mean value of 7.26 kWh/m^2 in the south. The mean yearly sunshine duration varies from a low of 2650 h on the coastal line to 3500 h in the south. With this huge quantity of sunshine per year, Algeria is one of the countries with the highest solar radiation levels in the world [28].

2.1.2. Observed climate data

The retained models were evaluated and tested for six Algerian sites with the three different climates (Fig. 1). Detailed geography, and the time period from which data were used for establishing the models as well as evaluating them of these sites are given in Table 2.

In this work, the measured global radiation data (mJ m^{-2} day^{-1}), as well as the sunshine duration (h), and the air temperatures (°C) for the selected sites, were obtained from Algerian National Office of Meteorology (NOM), in addition to the Center for the Renewable Energy Development (Algiers) and its annexes of Ghardaia and Adrar

2.2. Methodology

2.2.1. Model introduction

The most commonly used parameter for estimating global solar radiation is sunshine duration, and the previous studies have indicated that the models based on sunshine hours can

Table 1
Solar potential in Algeria [28].

Areas	Coastal area	High plains	Sahara	Total
Surface (%)	4	10	86	100
Area (km^2)	95,270	238,174	2,048,297	2,381,741
Mean daily sunshine duration (h)	7.26	8.22	9.59	
Average duration of sunshine (h/year)	2650	3000	3500	
Received average energy (kWh/m^2/year)	1700	1900	2650	
Solar daily energy density (kWh/m^2)	4.66	5.21	7.26	
Potential daily energy (TWh)	443.96	1240.89	14,870.63	16,555.48

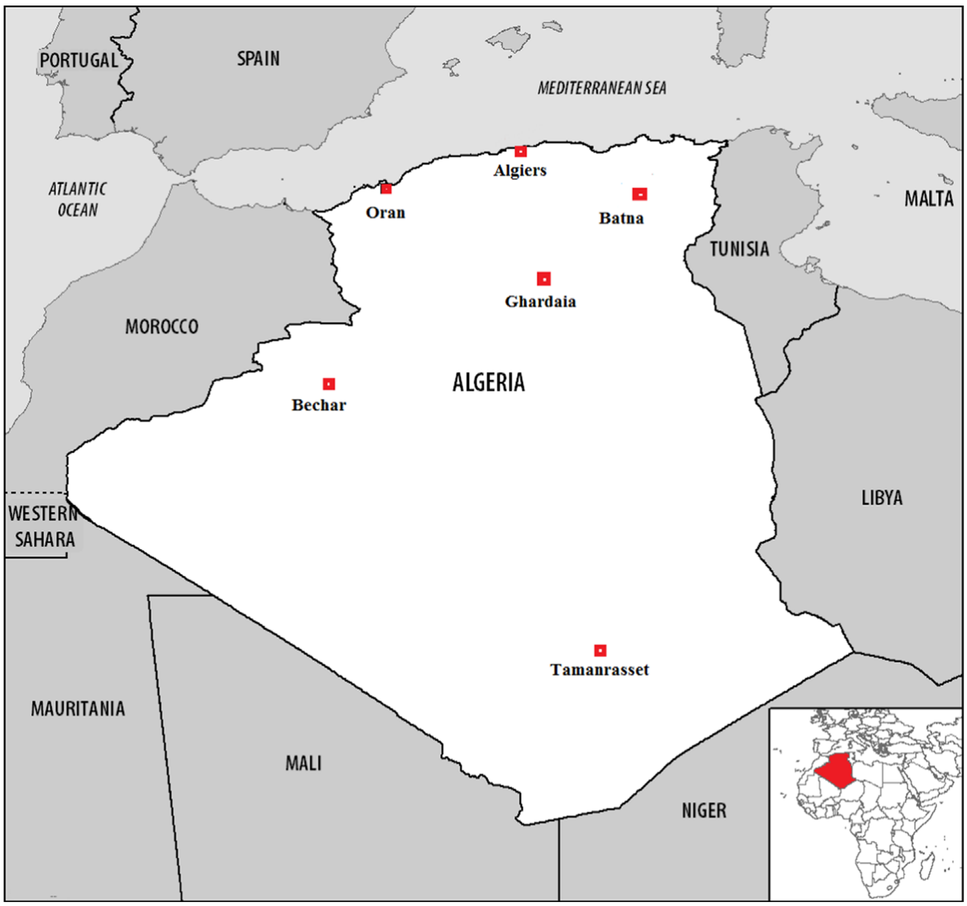

Fig. 1. Location of the stations considered on the map of Algeria.

Table 2
Geographic and data records period of the studied stations.

Sites	Latitude (N°)	Longitude (E°)	Altitude (m)	Sunshine duration (h)	Mean T_{min} (°C)	Mean T_{max} (°C)	Data series for establishing models	Data series for evaluating models
Algiers	36.43	3.15	25	7.79	12.41	24.24	1990–1992	2009–2011
Oran	35.38	−0.7	99	7.89	12.26	23.47	1990–1992	2009–2011
Batna	35.76	6.32	821	7.91	8.21	22.98	1990–1992	2009–2011
Ghardaia	32.36	3.81	450	8.86	15.46	29.51	2005-2006	2007–2009
Bechar	31.38	−2.15	806	9.78	14.97	27.44	2009-2010	2011
Tamanrasset	22.783	5.516	1377	8.92	15.36	29.42	1995–2005	2006–2011

provide more accurate estimations of solar radiation than those based on air temperature [19,20,29,30]. Consequently, this study mainly focused on the sunshine based models. However, models based on air temperature may be used in case of location without measuring sunshine data. The other required parameters such as extraterrestrial radiation and maximum possible sunshine hours are worked out using the standard following relations [2,31,32]:

$$H_0 = \left(\frac{24 \times 60}{\pi}\right) I_{sc} d_r [\cos(\varphi)\cos(\delta)\sin(\omega_s) + \omega_s \sin(\varphi)\sin(\delta)]$$

$$d_r = 1 + 0.033\cos\left(\frac{2\pi}{365} J\right)$$

Table 3
Regression models based on sunshine duration used in the paper.

Models	Model no. #	Regression equations	Source
Linear	1	$\left(\frac{H}{H_0}\right)=a+b\left(\frac{S}{S_0}\right)$	Angstrom [11], Prescott [12]
Quadratic	2	$\left(\frac{H}{H_0}\right)=a+b\left(\frac{S}{S_0}\right)+c\left(\frac{S}{S_0}\right)^2$	Akinoglu and Ecevit [33]
Cubic	3	$\left(\frac{H}{H_0}\right)=a+b\left(\frac{S}{S_0}\right)+c\left(\frac{S}{S_0}\right)^2+d\left(\frac{S}{S_0}\right)^3$	Bahel et al. [34]
Logarithmic	4	$\left(\frac{H}{H_0}\right)=a+b\log\left(\frac{S}{S_0}\right)$	Ampratwum and Dorvlo [35]
Exponential	5	$\left(\frac{H}{H_0}\right)=ae^{b\left(\frac{S}{S_0}\right)}$	Elagib and Mansell [36]
Exponent	6	$\left(\frac{H}{H_0}\right)=a\left(\frac{S}{S_0}\right)^b$	Bakirci [32]

Table 4
Regression models based on air temperature used in the paper.

Models	Model no. #	Regression equations	Source
Allen (1)	7	$\left(\frac{H}{H_0}\right)=0.17\sqrt{\left(\frac{293-0.0065Alt}{293}\right)^{5.26}}\sqrt{T}$	Allen [37]
Hargreaves	8	$\left(\frac{H}{H_0}\right)=a+b\sqrt{T}$	Hargreaves and Samani [13]
Chen (1)	9	$\left(\frac{H}{H_0}\right)=a+b\sqrt{\Delta T}$	Chen et al. [29]
Chen (2)	10	$\left(\frac{H}{H_0}\right)=a+b\log T$	Chen et al. [29]
Allen (2)	11	$\left(\frac{H}{H_0}\right)=aT^b$	Allen [38]

T: Mean air temperature, $T=(T_{max}-T_{min})/2$.
ΔT: Diurnal range air temperature, $\Delta T=T_{max(i)}-(T_{min(i)}+T_{min(i+1)})/2$.
Alt: Altitude.

$$\delta=0.4093\ \sin\left[\frac{2\pi}{365}(248+J)\right]$$

$$\omega_s=\text{arc cos}\ [-\ \tan(\varphi)\tan(\delta)]$$

Where d_r relative earth–sun distance, δ solar declination (rad), ω_s sunset hour angle (rad), φ latitude (rad), and J is the number of day in the year that taken from Table 1.6.1 [31].

I_{sc} is the solar constant as 0.082 MJ/m^2/min (1367 W/m^2) [2].

Eleven models selected from the literature and classified in 2 different categories:

Category (1): Sunshine based models.

The first correlation model is Angstrom–Prescott model (model 1 in Table 3), which has been the most convenient and widely used correlation for estimation of solar radiation based on sunshine duration.

In this study, six regression models based on sunshine duration that derived from the Angstrom–Prescott model, were examined and validated to predict monthly mean daily global solar radiation on a horizontal surface, and are listed in Table 3.

Category (2): Air temperature based models.

When the locations of interest do not have sunshine duration records; air daily temperature, a common worldwide measured parameter, can be used to estimate the monthly mean global radiation values [19]. Hargreaves and Samani [13] proposed an equation (model 2 in Table 4) using daily maximum (T_{max}) and minimum (T_{min}) temperatures. This model was modified by many others. Five regression models based on air temperature were chosen for this study, and are presented in Table 4.

2.2.2. Model evaluation

The correlation coefficients of the ten regression models (1–7, 8–11) were estimated by curve estimation techniques with statistical programs for the six sites. In this paper, six performance indicators were used for model comparisons, namely, coefficient of determination (R^2), mean percent error (MPE), mean absolute percent error (MAPE), mean bias error (MBE), mean absolute bias error (MABE), and root mean square error (RMSE). These parameters are the most widely used by researchers that mentioned in the literature to control the performance of the solar radiation regression models. These performance indices are calculated using the following equations:

$$R^2=\frac{\sum_{i=1}^{n}(Y_{i,m}-Y_{i,c})^2}{\sum_{i=1}^{n}(Y_{i,m}-\overline{Y}_{i,m})^2}$$

$$\text{MPE}=\frac{1}{n}\sum_{i=1}^{n}\left(\frac{Y_{i,m}-Y_{i,c}}{Y_{i,m}}\right)100$$

$$\text{MAPE}=\frac{1}{n}\sum_{i=1}^{n}\left(\left|\frac{Y_{i,m}-Y_{i,c}}{Y_{i,m}}\right|\right)100$$

$$\text{MBE}=\frac{1}{n}\sum_{i=1}^{n}(Y_{i,m}-Y_{i,c})$$

$$\text{MABE}=\frac{1}{n}\sum_{i=1}^{n}(|Y_{i,m}-Y_{i,c}|)$$

$$\text{RMSE}=\frac{1}{n}\sqrt{\sum_{i=1}^{n}(Y_{i,m}-Y_{i,c})^2}$$

Where $Y_{i,m}$, $Y_{i,c}$, $\overline{Y}_{i,m}$ and n are the measured clearness index $\left(\frac{H_m}{H_0}\right)$, calculated clearness index $\left(\frac{H_c}{H_0}\right)$, the average of the measured clearness index and the number of observations respectively.

3. Results and discussion

The eleven models established and evaluated, and the regression coefficients of the 10 models for the six sites obtained have been presented in Tables 5–10, then, for the six nominated sites and for all models the statistical indicators were calculated using the evaluation independent data series.

3.1. Site-dependent models

3.1.1. Algiers

As shown in Table 5 and Fig. 2, and for category 1, the highest coefficient of determination (R^2) of the calculated and measured clearness index (H/H_0) at the Algiers station is obtained as 0.8659 with cubic regression model, while the lowest value of correlation coefficient acquired by logarithmic regression (#4) as 0.7014.

For Algiers the best result in category 1 (sunshine based models) was acquired for cubic model (#3), the ideal values of statistical tests such as MPE, MAPE, MBE, MABE and RMSE are 0 or closer to 0 that mentioned previous studies [2]. In this study the lowest values of the MPE, MAPE, MBE, MABE and RMSE are derived by the cubic regression model as 0.0748, 3.2259, −0.0004, 0.0167 and 0.0197, respectively for the Algiers station (Table 5). Moreover, the best result in category 2 (air temperature based models) was obtained from Chen 1 model (#9) with a coefficient of determination R^2=0.8659, MPE, MAPE, MBE, MABE and RMSE are 0.0281, 4.9139, −0.0023, 0.0265 and 0.0368 respectively, while the worst performances are those of Allen 1 (#7) with R^2=0.3749.

Table 5
Regression constants and statistical results of each model for Algiers.

Model no.	*a*	*b*	*c*	*d*	R^2	MPE	MAPE	MBE	MABE	RMSE
1	0.271	0.408			0.7491	0.1995	4.0313	−0.0003	0.0215	0.0269
2	0.928	−1.750	1.713		0.8635	0.0224	3.2683	−0.0007	0.0170	0.0198
3	1.663	−5.373	7.533	−3.081	0.8659	0.0748	3.2259	−0.0004	0.0167	0.0197
4	0.644	0.243			0.7014	0.1615	4.5198	−0.0007	0.0242	0.0293
5	0.325	0.761			0.7690	−0.0159	3.8189	−0.0014	0.0204	0.0259
6	0.653	0.455			0.7241	0.0379	4.3472	−0.0014	0.0233	0.0283
7					0.5214	11.0881	11.9725	0.0543	0.0598	0.0696
8	−0.303	0.242			0.3749	0.5383	6.8048	−0.0004	0.0366	0.0424
9	−0.185	0.208			0.5310	0.0281	4.9139	−0.0023	0.0265	0.0368
10	−0.487	0.411			0.3750	0.2402	6.7876	−0.0020	0.0366	0.0425
11	0.076	0.782			0.3746	−0.2769	6.6916	−0.0047	0.0363	0.0427

Table 6
Regression constants and statistical results of each model for Oran.

Model no.	*a*	*b*	*c*	*d*	R^2	MPE	MAPE	MBE	MABE	RMSE
1	0.104	0.677			0.7768	0.2066	5.4014	−0.0010	0.0286	0.0349
2	0.712	−1.227	1.460		0.8029	0.3249	5.4007	−0.0003	0.0291	0.0328
3	15.57	−70.09	106.30	−52.58	0.8653	−5.1676	6.3569	−0.0298	0.0357	0.0409
4	0.734	0.428			0.7547	0.4044	5.6728	−0.0002	0.0301	0.0366
5	0.243	1.228			0.7893	0.1454	5.2963	−0.0014	0.0281	0.0340
6	0.762	0.779			0.7725	0.2142	5.5885	−0.0013	0.0298	0.0353
7					0.2760	6.1653	13.7346	0.0231	0.0717	0.0786
8	1.339	−0.237			0.2760	2.3024	12.1926	0.0029	0.0662	0.0733
9	0.082	0.138			0.2562	1.3329	11.3884	−0.0011	0.0620	0.0679
10	1.495	−0.390			0.2731	3.6183	12.5699	0.0099	0.0674	0.0739
11	4.065	−0.830			0.2684	2.5937	12.2538	0.0044	0.0644	0.0734

Table 7
Regression constants and statistical results of each model for Batna.

Model no.	*a*	*b*	*c*	*d*	R^2	MPE	MAPE	MBE	MABE	RMSE
1	0.345	0.329			0.9475	−0.2005	1.1958	−0.0012	0.0067	0.0075
2	0.578	−0.384	0.537		0.9637	0.0244	0.8672	0.0001	0.0048	0.0062
3	2.003	−6.883	10.290	−4.826	0.9682	−0.3569	0.8028	−0.0021	0.0045	0.0062
4	0.654	0.214			0.9291	−0.0720	1.3853	−0.0005	0.0077	0.0086
5	0.383	0.581			0.9527	−0.0668	1.1010	−0.0005	0.0061	0.0070
6	0.660	0.377			0.9368	−0.0494	1.3088	−0.0004	0.0073	0.0081
7					0.7133	10.5550	10.5550	0.0596	0.0596	0.0664
8	0.228	0.086			0.7133	−0.5118	2.6850	−0.0034	0.0150	0.0176
9	0.268	0.076			0.7641	−0.4094	2.3048	−0.0027	0.0130	0.0159
10	0.125	0.162			0.6884	−0.2170	2.7260	−0.0018	0.0151	0.0181
11	0.260	0.285			0.7029	−0.2994	2.6889	−0.0023	0.0150	0.0178

Table 8
Regression constants and statistical results of each model for Ghardaia.

Model no.	*a*	*b*	*c*	*d*	R^2	MPE	MAPE	MBE	MABE	RMSE
1	0.717	−0.039			0.5131	0.0513	2.6687	−0.0004	0.0183	0.0225
2	2.479	−4.940	3.382		0.6991	0.0392	2.1445	−0.0002	0.0147	0.0176
3	8.097	−28.62	36.47	−15.32	0.7261	0.6559	2.0957	0.0041	0.0143	0.0176
4	0.677	−0.03			0.5866	−0.2407	2.6560	−0.0024	0.0183	0.0226
5	0.716	−0.05			0.5152	0.3229	2.6822	0.0015	0.0184	0.0226
6	0.677	−0.05			0.5903	−0.0603	2.6700	−0.0011	0.0184	0.0225
7					0.5245	−9.8831	9.8831	−0.0683	0.0683	0.0729
8	0.437	0.067			0.5245	0.0138	2.4788	−0.0005	0.0171	0.0199
9	0.764	−0.2			0.5807	0.2425	2.6578	0.0009	0.0183	0.0223
10	0.361	0.123			0.5219	−0.3229	2.4759	−0.0028	0.0171	0.0202
11	0.426	0.181			0.5229	−0.1306	2.4784	−0.0015	0.0171	0.0200

3.1.2. Oran

For Oran the best result in category (1) was obtained for the cubic model (#3) with 0.8653 as a coefficient of determination (R^2), MPE = −5.1676, MAPE = 6.3569, MBE = −0.0298, MABE = 0.0357 and RMSE = 0.0409. While the worst result was obtained for the logarithmic model (#4) with R^2 = 0.7547. Moreover, the best result in category (2) was obtained for the Hargreaves model (#8) with R^2 = 0.2760 and 2.3024, 12.1926, 0.0029, 0.0662 and

Table 9
Regression constants and statistical results of each model for Bechar.

Model no.	*a*	*b*	*c*	*d*	R^2	MPE	MAPE	MBE	MABE	RMSE
1	1.012	−0.405			0.8143	−1.0263	2.0685	−0.0073	0.0142	0.0164
2	11.63	−26.88	16.47		0.8144	0.1512	1.8006	0.0007	0.0123	0.0147
3	20.83	−61.3	59.38	−17.81	0.6001	−0.3051	2.0274	−0.0025	0.0140	0.0179
4	0.614	−0.32			0.5964	0.3136	2.0206	0.0017	0.0138	0.0178
5	1.097	−0.58			0.6032	−0.1588	2.0024	−0.0015	0.0138	0.0177
6	0.618	0.47			0.6032	−0.1588	2.0024	−0.0015	0.0138	0.0177
7					0.6343	−16.1474	16.1474	−0.1109	0.1109	0.1136
8	0.916	−0.066			0.6343	0.0521	2.3992	−0.0003	0.0165	0.0208
9	0.707	−0.006			0.4818	0.4837	2.5117	0.0027	0.0172	0.0212
10	0.972	−0.11			0.6252	1.7408	3.1219	0.0113	0.0212	0.0236
11	1.037	−0.16			0.6224	1.4637	2.9775	0.0094	0.0202	0.0228

Table 10
Regression constants and statistical results of each model for Tamanrasset.

Model no.	*a*	*b*	*c*	*d*	R^2	MPE	MAPE	MBE	MABE	RMSE
1	0.529	0.210			0.5970	−1.9362	2.9986	−0.0141	0.0210	0.0256
2	−0.173	2.126	−1.284		0.7121	0.2238	2.0559	0.0011	0.0143	0.0169
3	−1.806	8.705	−10.030	−3.848	0.7180	0.8010	2.0725	0.0051	0.0143	0.0175
4	0.734	0.159			0.6210	−0.0025	2.2765	−0.0005	0.0158	0.0188
5	0.544	0.309			0.5911	−0.1341	2.3231	−0.0014	0.0162	0.0194
6	0.736	0.233			0.6157	0.0406	2.3072	−0.0002	0.0160	0.0189
7					0.6869	−14.6435	14.6435	−0.1008	0.1008	0.1024
8	0.235	0.120			0.6869	−0.3917	2.1732	−0.0031	0.0151	0.0177
9	0.659	0.007			0.2297	−0.1924	3.4322	−0.0024	0.0237	0.0272
10	0.094	0.224			0.6871	−0.2938	2.1608	−0.0025	0.0150	0.0176
11	0.289	0.327			0.6870	−0.2719	2.1568	−0.0023	0.0149	0.0176

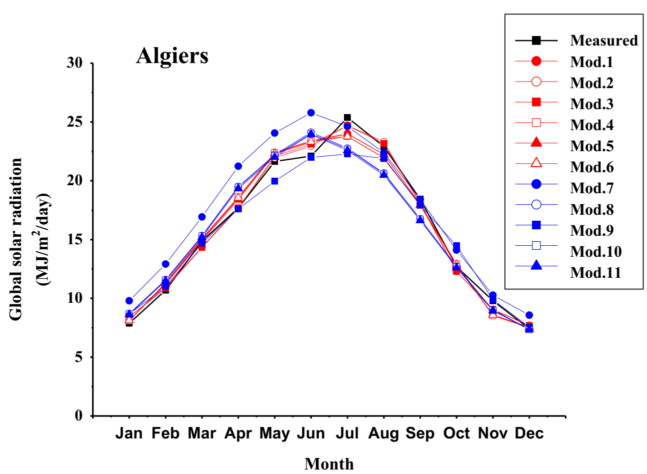

Fig. 2. Comparison between the measured and predicted monthly mean daily global solar radiation in Algiers.

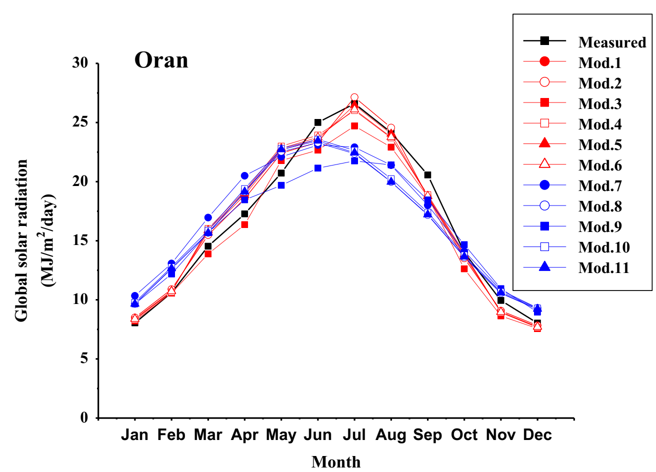

Fig. 3. Comparison between the measured and predicted monthly mean daily global solar radiation in Oran.

0.0733 for MPE, MAPE, MBE, MABE and RMSE respectively. While the worst result is shown with Chen1 model (#9) with a coefficient of determination $R^2=0.2562$ (Table 6 and Fig. 3).

3.1.3. Batna

As shown in Table 7 and Fig. 4, for Batna the best result in sunshine based models was acquired for cubic model (#3), with the lowest values of the MPE, MAPE, MBE, MABE and RMSE are derived from this model as −0.3569, 0.8028, −0.0021, 0.0045 and 0.0062 respectively, and coefficient of determination $R^2=0.9682$. While the worst model in the same category is the Logarithmic model (#4) with $R^2=0.9291$.

For the air temperature based model, the best result is for Chen 1 model (#9) with $R^2=0.7641$, and −0.4094, 2.3048, −0.0027, 0.0130 and 0.0159 for MPE, MAPE, MBE, MABE and RMSE respectively. The worst model is Allen1 model (#7) with a coefficient of determination $R^2=0.7133$.

3.1.4. Ghardaia

For Ghardaia, the best result in category (1) was obtained for the cubic model (#3) with $R^2=0.7261$, MPE=0.6559, MAPE=2.0957, MBE=0.0041, MABE=0.0143, and RMSE=0.0176. While the worst result in the same category was obtained from the linear model (#1) with a coefficient of determination $R^2=0.5131$. Likewise, the best result in category (2) was obtained from Chen 1 model (#9) with $R^2=0.5807$, MPE=0.0138, MAPE=2.4788, MBE=−0.0005, MABE=0.0171 and RMSE=0.0199, and the worst result was for Allen1 (#7) with $R^2=0.5245$ (Table 8, Fig. 5).

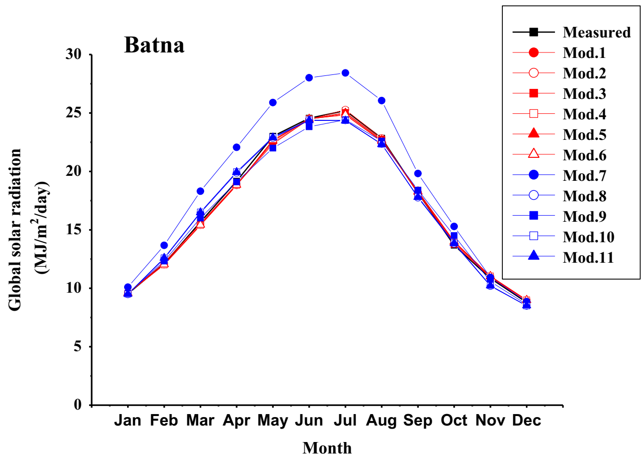

Fig. 4. Comparison between the measured and predicted monthly mean daily global solar radiation in Batna.

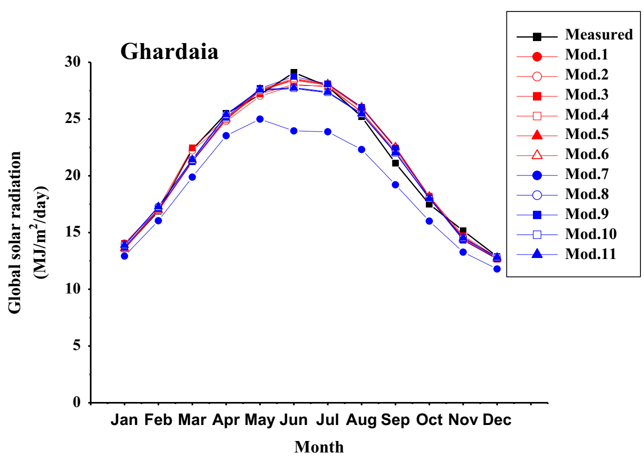

Fig. 5. Comparison between the measured and predicted monthly mean daily global solar radiation in Ghardaia.

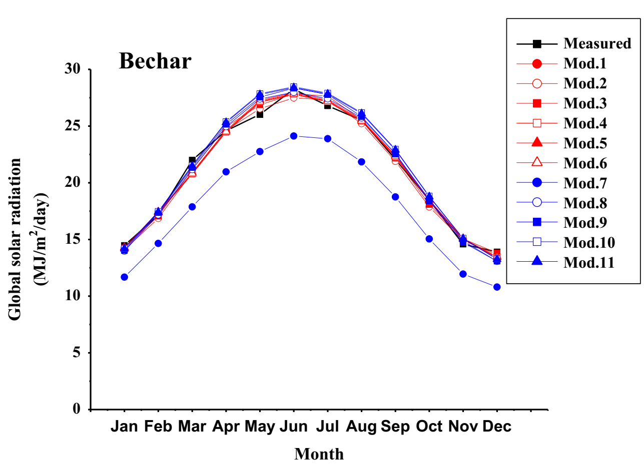

Fig. 6. Comparison between the measured and predicted monthly mean daily global solar radiation in Bechar.

3.1.5. Bechar

As shown in Table 9, for Bechar the best result in category 1 (sunshine based models) was acquired for the quadratic model (#2), the high value of R^2=0.8144 and lowest values of MPE, MAPE, MBE, MABE and RMSE are derived from the same regression model as 0.1512, 1.8006, 0.0007, 0.0123 and 0.0147, respectively, while the worst result for the logarithmic model (#4) with

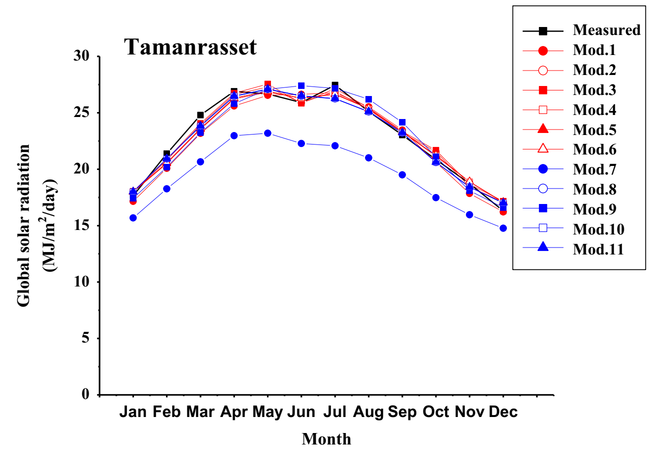

Fig. 7. Comparison between the measured and predicted monthly mean daily global solar radiation in Tamanrasset.

R^2=0.5964 (Table 9, Fig. 6). Moreover, the best result in category 2 (air temperature based models) was obtained for the Hargreaves model (#8) with coefficient of determination=0.6343 and MPE, MAPE, MBE, MABE and RMSE are 0.0521, 2.3992, −0.0003, 0.0165 and 0.0208 respectively, while the worst models are those of Allen1 (#7) with R^2=0.6343.

3.1.6. Tamanrasset

For Tamanrasset, the best result in category (1) was obtained for the quadratic model (#2) with R^2=0.7121, MPE=0.2238, MAPE=2.0559, MBE=0.0011, MABE=0.0143, and RMSE=0.0169. While the worst result in the same category was obtained from the exponential model (#5) with a coefficient of determination R^2=0.5911. Likewise, the best result in category (2) was obtained from Chen 2 model (#10) with R^2=0.6871, and MPE, MAPE, MBE, MABE and RMSE are −0.2938, 2.1608, −0.0025, 0.0150 and 0.0176 respectively, and the worst result was for Allen1 model (#7) with R^2=0.6869 (Table 10, Fig. 7).

3.2. General models

It can be seen that the correlation coefficients of the ten models are site-dependent. Therefore, for most locations in Algeria with unavailable data of global solar radiation, general models for predicting the monthly mean daily global solar radiation are needed.

It could be reasonable to recommend the models based on sunshine records data (models #2 and #3), to use it as general models for estimation the global solar radiation on horizontal surface over Algeria on the basis of their performances. Multiple linear regression analysis was used to develop the generalized coefficients for model 2, 3 using sunshine records and then validated over the six stations with available data of solar radiation; the performances of these two generalized models after validation were given in Table 11. The two general models for estimating the monthly mean daily global solar radiation in Algeria are, respectively, developed as follows:

$$\left(\frac{H}{H_0}\right) = 0.57089 + 0.01028\left(\frac{S}{S_0}\right) - 0.00005\left(\frac{S}{S_0}\right)^2$$

$$\left(\frac{H}{H_0}\right) = 0.57211 + 0.00901\left(\frac{S}{S_0}\right) + 0.00028\left(\frac{S}{S_0}\right)^2 - 0.00002\left(\frac{S}{S_0}\right)^3$$

As shown in Table 11, the averaged R^2 values of these two models with the six stations are 0.7264 for the quadratic model and 0.7257 for the cubic model. The highest coefficient of

Table 11
Statistical results of the two general models for the six Algerian stations.

Location	Model	R^2	MPE	MAPE	MBE	MABE	RMSE
Algiers	Quadratic	0.7489	10.1786	12.6623	0.0482	0.0635	0.0714
	Cubic	0.7558	10.2836	12.7316	0.0487	0.0638	0.0718
Oran	Quadratic	0.7698	8.3142	14.4408	0.0348	0.0743	0.0809
	Cubic	0.7786	8.416	14.4955	0.0353	0.0745	0.0812
Batna	Quadratic	0.9461	3.3201	5.6390	0.0168	0.0310	0.0356
	Cubic	0.9516	3.4149	5.7009	0.0173	0.0313	0.0359
Ghardaia	Quadratic	0.5181	−15.8761	15.8761	−0.1099	0.1099	0.1123
	Cubic	0.5112	−15.8108	15.8108	−0.1095	0.1095	0.1118
Bechar	Quadratic	0.6877	−15.1493	15.1493	−0.1041	0.1041	0.1062
	Cubic	0.6726	−15.0895	15.0895	−0.1037	0.1037	0.1058
Tamanrasset	Quadratic	0.6880	−15.7193	15.7193	−0.1089	0.1089	0.1121
	Cubic	0.6844	−15.6522	15.6522	−0.1085	0.1085	0.1117

determination (R^2) of the calculated and measured clearness index (H/H_0) is obtained as 0.9516 with the quadratic regression model for Batna, while the lowest value of correlation coefficient acquired by the cubic regression as 0.5112 for Ghardaia.

Moreover, as shown in Table 11, the lowest value of the RMSE is derived by the quadratic model for Batna as 0.0356, while the highest value is obtained by the quadratic model for Ghardaia as 0.1123. The lowest values of the MPE, MAPE, MBE, and MABE are derived by the quadratic model from the same station of Batna as MPE=3.3201, MAPE=5.639, MBE=0.0168, and MABE=0.0310, while the highest values of MPE, MAPE, MBE, and MABE are derived by the quadratic model from Ghardaia station as MPE=−15.8761, MAPE=15.8761, MBE=−0.1099, and MABE=0.1099.

4. Conclusion

In this study, 11 different models classified into 2 categories (6 sunshine and 5 air temperature based models) were nominated from the literature. After performing regression analysis and evaluating these models with six statistical parameters, the best model for estimation global solar radiation on horizontal surface has been introduced for each of the six stations. The results of this study show that the sunshine based models (with coefficients of determination for the six stations varied from the lowest value of 0.5131 to the highest one with 0.9682) are generally more accurate than air temperature based models (with R^2 varied from 0.2297 to 0.7641), and the best performances were obtained from the cubic and quadratic models; with the highest mean coefficients of determination of 0.8092 and 0.7906 respectively. Therefore, they can be used to predict monthly mean daily global solar radiation on a horizontal surface. Moreover, these two regression models can be used for the proposed generalized models for predicting the monthly mean global solar radiation in Algerian locations with the absence of the measured solar radiation data.

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